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INTERPRETING FOREST AND GRASSLAND BIOME PRODUCTIVITY UTILIZING NESTED SCALES OF IMAGE RESOLUTION AND BIOGEOGRAPHICAL ANALYSIS

Section of Botany and Plant Pathology Technical Report

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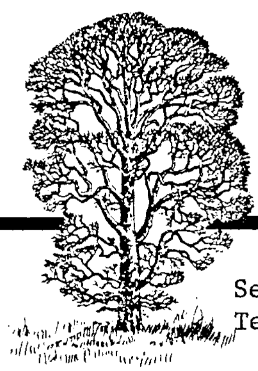

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THEMATIC MAPPER WORKING GROUP PROGRESS REPORT 3

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NASA Contract #NAS5-28781

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PART I INVESTIGATION AND TECHNICAL PLAN

A. SUMMARY

This report summarizes progress made in our investigation of forest productivity assessment using TM and other biogeographical data during the third six-month period of the grant. Data acquisition and methodology hurdles are largely complete. Four study areas for which the appropriate TM and ancillary data were available are currently being intensively analyzed. Significant relationships have been found on a site by site basis to suggest that forest productivity can be qualitatively assessed using TM band values and site characteristics. Perhaps the most promising results relate TM unsupervised classes to forest productivity, with enhancement from elevation data. During the final phases of the research, multi-temporal and regional comparisons of results will be addressed, as well as the predictability of forest productivity patterns over a large region using TM data and/or TM nested within AVHRR data.

B. INTRODUCTION

In this third semi-annual report, we briefly describe progress made over the past six months on our TM project. To fully understand the scope and objectives of the work reported, reference should be made to earlier progress reports filed in February 1986 and August 1986.

In reports 1 and 2, we mentioned a number of potential study sites for which data availability were being assessed. As the project has evolved, four sites have become the most intensively researched due to data that are available for the areas and collaboration with other scientists studying in those regions. The intensive study sites are Boulder county watershed, Colorado; southern Illinois including Jackson and Pope counties; the Cades Cove area of the Great Smoky Mountain National Park; and Huntington Wildlife Forest in Adirondack Park. This third report is devoted nearly entirely to work on these four areas, where significant progress has been made.

The report is divided into two parts: Part I Investigations and Technical Plan, and Part II Appendices. In Part I we discuss data acquisition, research approach, results, and future research directions. Part II includes references, background material on one intensive study site, abstracts pertaining to this work that we have submitted to professional meetings, pertinent seminars, meeting attendance, and publications of the investigators, and a copy of a completed manuscript from this research.

C. DATA ACQUISITION

1. Forest Productivity Data

a. Cades Cove Area--Great Smoky Mountain National Park

In October 1986 we remeasured eight 1/20th ha long-term forest productivity plots in the Great Smoky Mountains National Park. These plots were established in 1977 by Drs Jerry Olson and Rudolf Becking to provide data on long-term trends in forest productivity (Becking and Olson 1978). Ours was the first remeasurement although we know the 1960 basal area, species composition and diameter distributions of 5 of the plots (Whittaker 1966). At each plot we measured diameter at breast height (bh=1.3m) of every tree greater than 1 cm at dbh. The trees had been tagged and measured in 1977 so we knew the 1977 dbh. The 1977 and 1986 data were converted to aboveground standing biomass through the use of species specific biomass equations available in the literature. Wherever possible, we selected equations which were derived from tree biomass collections taken in the Appalachian area and with a diameter range the same as ours. In a few cases it was not possible to meet both criteria in which case we chose an equation of a species with a like growth form and the appropriate dbh range. Productivity was calculated as the change in live aboveground biomass + mortality + leaffall. The calculated productivity values for the eight sites are shown below.

Along with their use in evaluating the feasibility of using TM data to predict forest productivity, these productivity values have intrinsic scientific merit. Virtually no actual measures of forest productivity exist of virgin cove forests such as we measured. We are currently writing a short paper to present these productivity data.

TABLE 1. Tree productivity and biomass on 8 1/20 ha plots in the Great Smoky Mountains National Park

PLOT	Type	Disturbance	Elev (ft)	Age (yr)	#Trees (#/ha)	Tree biomass (MT/ha)	Productivity (MT/ha/yr)
B1	Cove	none	2400	100+	1610	850	17.9
P1	Cove	farming	2400	<100	760	353	14.7
E2	Cove	none	2800	100	720	214	6.9
E1	Cove	none	3840	200+	330	337	7.4
M2	Cove	none	4300	200+	1070	690	12.6
C3	Oak	logging	2425	<100	1050	463	12.0
F2	Pine	logging	1925	80	1400	160	8.2
J2	Pine	none	3600	100	2890	88	5.3

b. Huntington Wildlife Forest--Adirondack Park

Through the gracious cooperation of the staff at Huntington Forest we have acquired the raw forest inventory data from almost 300 permanent forest inventory plots located in the forest. Of these plots, 195 have been measured more than once and thus can be used to evaluate productivity. At each fifth acre plot dbh was measured on all trees greater than 10.5 in dbh and on a quarter of the trees between

4.5 and 10.5 in dbh. We are currently converting the raw data to aboveground standing biomass through the use of species specific biomass equations available in the literature. Wherever possible, we have selected equations which were derived from tree biomass collections taken in the New York or New England area and with a diameter range the same as ours. In a few cases it was not possible to meet both criteria in which case we have chosen an equation of a species with a like growth form and the appropriate dbh range. Productivity is being calculated as the change in live aboveground biomass + mortality + leaffall. Thus far we have analyzed 173 of the 195 plots with remeasurement data. Plot productivities range from 2 to 16 MT/ha/yr. The remaining 22 plots will be analyzed as soon as we have the raw data entered on the computer. (The raw diameter data from the initial 173 plots were already on computer file). We have also acquired a map showing the approximate locations of the inventory plots in the forest and soon will be digitizing this map and extracting the UTM coordinates of the plots so we can pair pixel spectral with pixel productivity data. In addition to this map, we have received several other maps of the Huntington Wildlife Forest from our Syracuse collaborators. They include a detailed soils map, a vegetation/forest stand map, and a forest history map. With DEM data, we will also generate slope and aspect maps. In total, the Huntington site is emerging as our best study site considering the quantity and quality of available TM, GIS, and ground productivity data.

2. AVHRR

AVHRR data were acquired from the Satellite Data Services Division of NOAA to cover all potential study sites across the United States and Canada (see Table 3, Report 1). These data are of HRPT type from the NOAA-8 and NOAA-9 satellites, with the exception of the west coast sites--Emery, Oregon, Santa Barbara, and Sierra Nevada--which are LAC. September data were selected to maximize phenological differences among vegetative cover types. Table 2 lists latitude/longitude areas of coverage.

Because these data were received only a short time ago, we have not made significant progress integrating them with TM data. When AVHRR data pre-processing is complete, they will be calibrated with raw TM values and classified TM data that have established relationships to forest productivity to make similar assessments over larger regions.

3. Elevation Data

We have been attempting to acquire and read digital elevation data. It has been one of the most frustrating aspects of the project in that numerous incompatibility problems have been barriers to research progress. We have acquired DMA 1:250,000 data for all of Illinois and locations in California and South Dakota. We have also acquired 1:24,000 DEM data for a portion of the Boulder county (Colorado) area and the Cades Cove region of the Smokies. An order has been placed for 1:24,000 DEM data for the Huntington Wildlife Forest area and additional areas of Boulder county.

TABLE 2. AVHRR Data Acquired

Latitude/Longitude	Date	Areas Covered
+31 to +45/-098 to -087	9/6/85	Jackson,Pope,Calhoun,Lake, Grundy,Outagamie,Konza,Natchez
+34 to +44/-106 to -097	9/6/85	Custer,Konza,Boulder,Pawnee
+34 to +44/-105 to -098	9/11/85	Custer,Konza,Boulder,Pawnee
+42 to +50/-076 to -066	9/18/86	Whiteface,Huntington,Maine,Quebec
+30 to +38/-085 to -080	9/28/85	LeConte,Cades,Oak Ridge,Tall Timbers,Coweeta,Oconee, Okefenokee
+36 to +45/-093 to -091	9/7/85	Jackson,Pope,Calhoun,Lake,Grundy, Outagamie
+46 to +49/-094 to -091	9/23/85	Minnesota
+34 to +46/-110 to -122	9/3/86	Sierra Nevada,Emery, Oregon,Santa Barbara

D. RESEARCH APPROACH AND RESULTS

1. Data Handling Progress and Problems

a. Elevation Data

As mentioned previously, a number of DMA and DEM tapes have been or are being acquired. At present, we have one site with DEM data integrated with the other data. This is the Boulder county, Colorado, site where it has been possible to display mapped vegetation and classified TM image data in three dimensions. This is visually very informative to our analysis in regions where aspect has been shown to be a major parameter in estimating forest productivity.

Additional software is being written and/or obtained which will allow us to do the three dimensional work on more of our study sites. The major obstacle has been the inability to read tapes in various formats.

2. Analysis Results

a. Southern Illinois

Analysis was completed to determine the statistical relationships of TM band values, band ratios, and vegetative indexes to forest productivity estimates for 30 plots in southern Illinois (including the Jackson and Pope study sites and additional areas). Site characteristics such as soil productivity, aspect, slope, moisture regime, and sun radiance indexes were included in the analysis. Methodology, results, and discussion of this work are presented in the manuscript entitled "Estimating Forest Productivity in Southern Illinois Using Landsat Thematic Mapper Data and Geographic Information System Analysis Techniques" which is attached to this report as Appendix E. Because this manuscript is being published in the proceedings of the American Society for Photogrammetry and Remote Sensing (ASPRS) Annual Convention, we ask that it not be duplicated or cited from this report.

b. Cades Cove Area--Great Smoky Mountain National Park

Using forest growth and topography data from 128 plots in the Cades Cove area of The Great Smoky Mountains National Park and TM spectral data from one scene taken in September 1984 of the same area, we have examined the relationship between TM and forest productivity in the following two ways:

Method 1. Relationship between TM Band values and forest growth

After rectifying the scene, we identified those 128 TM pixels which most closely corresponded in UTM location to the centers of the 128 forest growth plots and extracted their band values. We also extracted the band values for the 8 surrounding pixels. We then paired the center pixel band values to the corresponding forest growth and topography values of each plot and used simple correlation analysis to examine the relationship between forest growth and TM and topographic data. Single band, band ratios and vegetation indexes were used. The analysis showed that:

a. Band 3 was the only single band that was significantly correlated with forest growth ($r=-.26$ $p<.0037$)

b. None of the vegetative indexes were correlated with forest productivity.

c. The ratio of band 6 to band 1 and the ratio of band 6 to band 3 had the best simple correlations with forest growth ($r= .36$ and $r= .35$ respectively)

d. Elevation was highly correlated with bands 1,2,5,6, and 7. Aspect was correlated with bands 1, 3 and 6.

e. The best correlations with forest growth were found on plots with northwest facing slopes which were shaded when the scene was taken.

f. 47% of the variance in forest growth of 35 northwest facing plots could be explained by a linear model of the ratio of band 6 to band 1 and the ratio of band 7 to band 3.

Method 2. Relationship between TM classes created by an unsupervised classification and forest growth

The rectified TM scene used in method 1 was clustered into 35 spectral classes using unsupervised classification. Of the 35 classes generated, 11 were related to forest, 14 were related to grass, 5 depicted forest-grass edges and 5 were water. The class values of the pixel and 8 surrounding pixels corresponding to the 128 forest growth plots were extracted from the classified scene. The most frequently occurring class in each set of 9 pixels was determined. In 87% of the 9 pixel sets, the center pixel (i.e. the pixel most closely associated with the actual plot location) was of the most frequently occurring class and in 72% of the sets 5 or more of the pixels were of the same class. We used the most frequent class in each 9 pixel set as the class type associated with the forest growth data. Six TM forest classes were associated with 6 or more forest growth plots and accounted for 125 of the 128 plots. We used an unbalanced 1-way ANOVA to determine if these 6 TM classes had significantly different forest growth. We also used a 1-way ANOVA to determine if the 6 TM classes had significantly different elevations. A 1-way (TM class) analysis of variance with elevation as a covariate with and without interactions was used to determine if TM class could significantly improve prediction of forest growth given elevation. Finally, the Chi-square test was used to determine if plot aspects were related to TM class. A two-way (aspect and TM class) analysis of variance with and without interactions was used to determine if aspect was significantly related to forest growth. The results of these analyses were as follows:

a. The TM classes had significant differences in mean forest growth. (means with like letters are not significantly different)

n	Class	mean (logn m^3/ha/yr)	
6	30	1.355	a
22	25	.899	ab
44	24	.870	ab
30	1	.535	cb
13	21	.130	cd
9	32	-.244	d

b. The TM classes had significant differences in mean elevation (means with like letters are not significantly different)

n	Class	mean (ft above sl)	
13	21	4640	a
9	32	3410	b
6	30	3220	bc
30	1	3101	bc
22	25	2801	bc
44	24	2613	c

c. Elevation is significantly and negatively correlated with forest growth.

d. There was no interaction between elevation and TM class in explaining forest growth. (i.e. the relationship between elevation and forest growth was the same within each TM class). There were significant differences in forest growth among TM classes even after the effect of elevation had been accounted for.

Forest growth by TM class adjusted for elevational differences (means with like letters are not significantly different)

n	Class	adjusted mean (logn m^3/ha/yr)	
6	30	1.395	a
44	25	.830	ab
22	24	.753	ab
30	1	.545	b
13	21	.539	cb
9	32	-.154	c

e. TM class was independent of plot aspect.

f. In a two-way ANOVA using TM class and aspect to predict forest growth, aspect was insignificant as was any aspect*TM class interaction.

The results of these analyses will allow us to create a productivity map of the Cades Cove area excluding those areas in which the pixels do not fall into classes 1,25,24,21,30, or 32. By overlaying a topographic map, we should be able to improve our productivity map by accounting for elevational effects. We are excited by these results as they are a solid indication that we can use TM data to at least qualitatively evaluate forest productivity over a landscape. Such an ability will allow us to address a wide variety of interesting landscape ecology questions such as how productivity is distributed over the landscape, what topographic factors appear to influence productivity patterns, and has disturbance altered those patterns.

c. Boulder County Watershed, Colorado

We are currently evaluating the topographic distribution of vegetation communities within the forest-alpine tundra ecotone using USGS digital elevation model data and digitized vegetation maps prepared by the Institute for Arctic and Alpine Research (INSTAAR) at the University of Colorado. The objective of this phase of our research is to determine how DEM data might be used to aid in the stratification of Thematic Mapper imagery prior to classification, or as image layers in a multi-band (spectral and topographic data) classification. In addition, we are developing topoclimatic indexes from the DEM that may prove useful for defining habitat characteristics of vegetation communities. If relationships between vegetation distribution and topoclimatic indexes emerge from this research, these may prove useful as other variables suited for classification improvement.

Both alpine tundra vegetation and forest species are being evaluated in this study because many forest patterns are intermixed with alpine meadows or alpine salix distributions. Part of our analysis will be to compare any classification problems between the alpine and forest categories. Topoclimate affects on alpine tundra and forest cover distributions are highly related in this study area, so information about both types are necessary to assess the usefulness of topoclimate indexes in classification procedures.

Since our analysis is now concentrating on topographic effects on vegetation distributions, we have developed a capability to display Thematic Mapper imagery and the vegetation maps in three-dimensional perspective views. This capability allows us to more readily evaluate whether relationships exist between topography and vegetation distributions. A good deal of our time over the past several months has been directed at software development. In addition to the 3D effort, we have written an image radiometric calibration program to compute radiance, reflectance and albedo from MSS and TM imagery. This program now allows us to use comparative data from multi-temporal imagery for assessing changes in productivity. This will be advantageous to the Huntington site where multi-temporal imagery, DEM data and forest productivity data exist. However, only albedo will be investigated as a single band image value for use in the Boulder County Watershed project to differentiate vegetation communities, because no productivity data or multi-temporal image data are available at this time. At present, we are working with only partial DEM coverage of the Ward, Colorado 7 1/2 minute quadrangle. This is limiting us to inadequate spatial coverage of all vegetation distributions because of snow cover in the July 1984 TM image. We are currently awaiting delivery of the full DEM from USGS before we can continue with a thorough analysis. However, some preliminary relationships are available from our small sample of vegetation relationships are available from our small sample of vegetation distributions, DEM and TM data sets. Thirty-one vegetation and cover categories identified on the INSTAAR maps are listed in Table 3. Descriptive statistics for initial topographic distributions for twenty-three categories are presented in Table 4.

Table 3. Vegetation and cover categories.

MEADOWS
1. Wet graminoid meadow - below timberline
2. Dry graminoid meadow - below timberline
3. Acomastylis Rossii alpine meadow
4. Acomastylis-Kobresia alpine meadow
5. Acomastylis-Kobresia alpine rock
6. Kobresia-Mysouroides alpine meadow
7. Carex-Kobresia alpine meadow
8. Carex-Cushion plant alpine rock

WILLOWS BELOW TIMBERLINE
9. Salix bog - below timberline
10. Salix moist meadow - below timberline
11. Salix rock meadow - below timberline

WATER
12. Water

WILLOWS ABOVE TIMBERLINE
13. Alpine Salix bog - above timberline
14. Alpine Salix moist meadow - above timberline
15. Alpine Salix rock meadow - above timberline

SHRUBS
16. Riparian shrub and Picea Pungens - below timberline

PREDOMINANTLY UNVEGETATED
17. Bare rock
18. Rock and sparse wet alpine - above timberline
19. Rock and sparse dry alpine - above timberline
20. Rock and sparse wet meadow - below timberline
21. Rock and sparse dry meadow - below timberline
22. Rock and sparse forest - below timberline
23. Rock and sparse Krummholz- within forest-alpine tundra ecotone

FOREST
24. Populus Tremuloides
25. Picea Engelmannii - Abies Lasciocarpa
26. Pinus Flexilis
27. Pinus Contorta
28. Pinus Ponderosa

OTHER
29. Krummholz conifers
30. Pseudotsuga Menziesii
31. Flagged Krummholz

Table 4. Vegetation distribution by elevation, slope and aspect. (not all classes are represented in available elevation data)

	ELEVATION				SLOPE				ASPECT			
	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD
1.	2784	3509	3109.0	105.0	0	38	10.0	6.6	0	328	139.9	75.1
2.	2805	2908	2864.0	24.8	9	32	17.8	4.3	124	189	147.4	12.2
3.	2816	3407	3059.9	132.5	0	33	11.5	5.7	0	328	119.7	69.9
4.	2801	3001	2867.9	44.3	0	23	8.8	4.5	0	311	86.3	40.4
5.	2983	3708	3382.8	106.9	0	57	17.2	8.4	0	327	104.5	91.4
6.	3308	3746	3462.1	69.0	0	36	11.8	4.8	0	328	162.2	95.0
7.	3057	3585	3274.5	183.2	9	41	19.2	5.1	0	326	98.8	75.1
8.	3220	3869	3523.9	119.3	0	63	17.7	10.5	0	328	132.5	106.4
9.	2787	3795	3185.9	174.2	0	44	10.4	8.0	0	327	131.4	72.3
10.	2784	3509	3113.1	102.1	0	38	9.8	6.5	0	328	141.3	74.3
11.	3408	3459	3437.9	12.0	0	14	6.9	3.5	0	327	155.0	144.7
14.	3266	3391	3323.2	28.0	7	22	14.3	2.9	113	240	173.2	30.0
16.	3081	3532	3284.1	76.3	0	46	15.4	8.8	0	328	146.0	83.4
18.	3223	3433	3351.4	52.8	1	44	12.5	3.9	0	327	65.1	79.2
19.	2965	3452	3241.3	103.5	8	28	17.6	3.7	0	325	122.5	68.1
21.	3081	4118	3656.6	188.4	0	69	32.3	12.5	0	328	154.8	100.6
23.	3062	3736	3286.1	156.2	0	46	4.7	5.5	0	327	147.3	85.7
24.	2889	3593	3135.4	99.3	0	42	12.1	7.1	0	328	128.4	69.8
25.	2854	3358	3141.6	98.1	0	45	13.8	7.3	0	328	125.9	72.9
28.	2946	3040	2996.4	21.7	0	22	8.3	4.9	7	326	80.0	56.3
29.	2977	3052	3028.4	20.9	2	14	8.2	3.1	72	120	96.4	10.7
30.	2898	3110	3041.9	59.4	0	21	8.4	4.4	24	299	95.4	52.0
31.	3250	3309	3273.5	14.6	1	14	6.4	2.6	1	327	53.6	72.6

Subsequently, signatures were derived for ten vegetation categories aggregated from the original twenty-five categories (Table 5) using TM bands 1, 2, 3, 4, 5 and 7; and one topoclimate index, slope-aspect index computed as:

SAI = SIN(slope) * aspect / SAIMAX * 255.

Where:

SAI is slope aspect
SAIMAX is maximum index value
255 maximum dynamic range or scale (8 bit image)

Standardized between signature distances (modified divergence -covariance weighted distance) using all bands and SAI value are presented in Table 6. Signatures were derived by overlaying a recoded vegetation image on the TM plus SAI image, and computing signatures for each vegetation category not covered by snow in the image.

Table 5. Aggregated vegetation categories.

1. Dry meadow
2. Fellfield
3. Moist shrub tundra
4. Moist meadow
5. Snowbed communities
6. Wet meadow
7. Scree slopes
8. Picea Engelmannii - Picea Abies
9. Pinus Flexilis
10. Mixed forest

Table 6. Standardized between signature distances

VEGETATION										
1.	0.00									
2.	8.16	0.00								
3.	6.52	14.76	0.00							
4.	12.09	3.80	18.83	0.00						
5.	17.62	9.66	24.13	6.11	0.00					
6.	17.42	9.42	23.96	5.85	0.28	0.00				
7.	30.69	22.85	37.21	19.57	13.03	13.37	0.00			
8.	14.01	6.16	20.39	2.61	3.27	3.01	16.07	0.00		
9.	17.26	6.30	26.25	1.31	6.77	6.42	24.31	2.19	0.00	
10.	10.49	19.18	3.64	23.56	28.95	28.80	42.65	24.94	33.21	0.00
$\bar{X}$	13.43	10.03	17.57	9.37	10.98	10.85	21.98	9.27	12.40	21.54

Further analysis of this type will be conducted when the full Ward quadrangle DEM becomes available. Until then, sample sizes for some vegetation categories are too small to interpret much from these tables. However, based on this analysis promising results seem likely for an analysis extended over a larger geographical region.

PART II APPENDICES

A. REFERENCES

Whittaker, R.H. 1966. Forest dimension and production in the Great Smoky Mountains. Ecology 47:103-121.

Becking, RW. and J.S. Olson. 1978. Remeasurement of permanent vegetation plots in the Great Smoky Mountains National Park, USA, and the implications of climatic change on vegetation. Oak Ridge National Laboratory, Oak Ridge TN 37831. Report # ORNL/TM-6083. 94 pg.

B. RESEARCH SITE BACKGROUND MATERIAL

1. Adirondack Park

The Adirondack Park consists of almost 2.4 million hectares in northeastern New York. The area is a patchwork of public and private land; forty percent is state-owned Forest Preserves, while the remaining sixty percent is private land used for agriculture, forestry, and recreation. The Adirondack Park Agency, a New York state agency with managerial authority for the Park, strives for a peaceful coexistence of preservation, recreation, and economic development of the area. The Park's large size, complex land ownership patterns, and combined management by state and local governments and citizen advisory all contribute to its uniqueness among U.S. state and national parks.

The southern and western Adirondacks are a gently rolling landscape dotted with many lakes and ponds. Proceeding northeastward, rugged mountains dominate, with 42 peaks over 1220 m. above sea level. The highest is Mount Marcy at 1630 m. Spruce/fir and northern hardwood associations such as beech/birch/maple comprise most of the Adirondack forests. Thirty tree species are native to the Park.

Huntington Wildlife Forest, a 6,000 hectare field station of the State University of New York (Syracuse) College of Environmental Science and Forestry, was selected as our intensive study site within Adirondack Park because of the extensive amount of data on site characteristics available from research done on the area. Huntington Wildlife Forest is rugged and mountainous, with elevations ranging from 475 m. to 820 m. above sea level. The mountains of the Forest have exposed bedrock and evidence of glacial scouring. Soils of the region are mostly glacial tills. The climate is cool and moist; the mean January temperature is -8.8 C and 18.8 C is average for July. Precipitation is uniformly distributed through the year although occasional summer droughts occur.

Huntington Wildlife Forest is nearly 90 percent forestland which is transitional between boreal forests and northern hardwoods. Approximately 70 percent of the forests are hardwoods, with 30 percent softwoods. Spruce and fir are common associates at higher elevations and are found together with eastern hemlock on poorly drained bottomlands. The northern hardwood associations (beech/birch/maple) dominate intermediate elevations where soils are deeper and better drained. Woody species that occur as the understory component of the hardwood association include hophornbeam, striped maple, honeysuckle, and witchhobble.

Approximately 10 percent of the Forest is water. There are 7 lakes on the area with the largest being 205 hectares. Less that 1 percent of the Forest's land cover is grass/fern openings and roads and buildings.

Forest productivity indexes have been calculated for 173 forest plots (as explained in Data Acquisition--Huntington) in the Huntington Wildlife Forest. Ancillary site characteristics available as maps include soils, elevation, aspect, vegetation and forest history. Two of these maps, soils and vegetation, were automated using ARC/INFO software and are being converted to ERDAS files for later overlay processing with the image data.

C. ABSTRACTS

Attached are six abstracts prepared by project personnel on topics directly concerning this work. They represent oral presentations that have or will be given at meetings of disciplines related to the project, and in most cases will result in a proceedings publication. By title, the meetings where these abstracts were submitted are as follows:

The Relationship of Forest Productivity to Landsat Thematic Mapper Data and Supplemental Terrain Information-- Pecora XI: Satellite Land Remote Sensing-Current Programs and a Look at the Future, Sioux Falls, SD

Evaluating Spatial Patterns of Forest Productivity in a Disturbed, Mountainous Landscape Using Landsat Data and a GIS
and
GIS and Remote Sensing as Tools for Detection of Landscape Pattern and Processes-- 1987 Annual Meeting, Ecological Society of America, Columbus, OH

Land Use Change in Illinois: The Influence of Soil Type on Current and Historic Land Use-- 2nd Annual Landscape Ecology Symposium, Charlottesville, VA

Evaluating Abandoned Pasture Patch Stability within a Forest Matrix Using Landsat TM Data and Historic Vegetation Maps--2nd International Seminar of the International Association of Landscape Ecology, Münster, West Germany

Assessing Forest Productivity in the Great Smoky Mountains National Park Using Thematic Mapper Spectral Data-- Third Annual Acid Rain Conference for the Southern Appalachians, Gatlinburg, TN

D. RELATED MEETINGS, SEMINARS, AND PUBLICATIONS SINCE AUGUST 1986

Cook, E. A., L. R. Iverson, and R. L. Graham. 1987. Estimating forest productivity in southern Illinois using Landsat thematic mapper data and geographic information system analysis techniques. Proceedings of the American Society of Photogrammetry and Remote Sensing (ASPRS) and the American Congress on Surveying and Mapping (ACSM) Annual Convention. (in press)

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Frank, T. D. 1986. Attended American Society of Photogrammetry and Remote Sensing (ASPRS) Fall Technical Conference. Anchorage, AK, October

Graham, R. L., L. R. Iverson, and E. Cook. 1986. Assessing forest productivity in the Great Smoky Mountains National Park using thematic mapper spectral data. Paper presented by Graham at the Third Annual Acid Rain Conference for the southern Appalachians, also attended by Iverson and Cook. Gatlinburg, Tennessee, 27-29 October

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E. SOUTHERN ILLINOIS ANALYSIS RESULTS--See attached manuscript

ABSTRACT

The Relationship of Forest Productivity to Landsat Thematic Mapper Data and Supplemental Terrain Information

Elizabeth A. Cook and Louis R. Iverson, Illinois Natural History Survey, Champaign, Illinois; and Robin L. Graham, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Research is being done to examine spectral data sensitivity to forest productivity and biomass. Approximately twenty study sites across the major forest regimes of North America are being studied. Two intensive study sites are located in southern Illinois and the Huntington Wildlife Forest in the central Adirondack Mountains, New York. The southern Illinois site consists of eastern deciduous and introduced conifer forests on level to rolling uplands and bottomland. Huntington Forest is a transitional boreal/northern hardwood forest in rugged, mountainous terrain.

Landsat Thematic Mapper (TM) data have been incorporated with spatial terrain information, such as soils, slope, vegetation types, and landforms, in a geographic information system (GIS) for each site. Also included in the data bases are the locations of ground forestry plots and their associated productivity and biomass measurements. Correlation and regression techniques are used to test the relationships of spectral values, band ratios, and vegetative indexes to measured productivity and productivity interpreted from the ancillary information (such as soil woodland productivity indexes).

This paper will discuss project methodology and results from the two sites. Discussion will focus on the value of TM data alone and with accompanying GIS information for predicting relative forest productivity. Consistency of results from multitemporal analysis at Huntington Forest and between the two sites will be discussed as an indication of the temporal and regional transferability of potential predictive models using TM data.

ABSTRACT FORM
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Author to contact: Robin L. Graham

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Address: Environmental Sciences Division
P.O. Box X, Building 1505, Oak Ridge, TN 37831-6038

Phone number: (615) 576-7756

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Tamalia coweni formed galls on developing leaves of Arctostaphylos insularis during the wet season on Santa Cruz Island, CA, but developing leaves were ....
vegetation acted as "oases" for Tamalia coweni infestations.

GRAHAM, ROBIN L., LOUIS R. IVERSON, and ELIZABETH A. COOK. Oak Ridge National Laboratory,[1] Oak Ridge, TN 37831, USA and Illinois Natural History Survey, Champaign, IL 61820, USA.

Evaluating spatial patterns of forest productivity in a disturbed, mountainous landscape using LANDSAT data and a GIS.[2]

An unsupervised classification of a LANDSAT Thematic Mapper (TM) scene of the Great Smoky Mountains National Park was done using all 7 spectral bands. The resulting TM class values for pixels ground-referenced to 128 forest productivity plots were extracted from the scene and paired with the plots' productivity values. The paired TM class/productivity values revealed significant differences in forest productivity between TM classes. On this basis the TM classes were reassigned to three productivity classes and a digitized forest productivity map of the entire TM scene generated. Using a Geographic Information System (GIS), this map was then overlaid with digitized topography and disturbance maps. Patterns of forest productivity were evaluated in reference to historic land disturbances and topography. Productivity information indices were calculated for each disturbance type.

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Author to contact: Dr. Louis R. Iverson

Institution: Illinois Natural History Survey

Address: 607 E. Peabody,
Champaign, IL 61820

Phone number: 217-333-6886

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IVERSON, LOUIS R., ELIZABETH COOK, and ROBIN L. GRAHAM. Illinois Natural History Survey, Champaign, IL 61820 and Oak Ridge National Laboratory, Oak Ridge, TN 37831.

GIS and remote sensing as tools for detection of landscape pattern and processes.

The Illinois Geographic Information System is equipped for GIS and image analysis which allows pursuit of many specific landscape-level questions. By overlaying historic vegetation maps with current maps, one can assess the factors contributing to long-term land-use change. GIS processing also provides for rapid determination of the suitability or susceptibility of phenomena occurring on landscapes. Examples of this type of processing include susceptibility to erosional soil loss or to crop yield reduction from droughts, and the suitability of various landscapes to provide adequate habitat for endangered plant species. The coupling of GIS processing with image analysis of satellite data provides a means for detecting changes and processes within landscapes. Some significant relationships have been uncovered, for example, among Landsat TM spectral data, site landscape variables, and ground-obtained forest productivity estimates.

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PROPOSED ABSTRACT

2nd Annual Landscape Ecology Symposium

Land Use Change in Illinois: The Influence of Soil Type on Current and Historic Land Use

Louis R. Iverson, Illinois Natural History Survey, Champaign, IL 61820

Illinois, more than nearly any other state, has seen drastic land use/vegetation change since European colonization in the early 1800s. These changes varied according to the soil patterns existing across the state. The Illinois Geographic Information System was used to assess the influence of the various soil types on current and historic land use patterns, at two different levels of resolution. Course-resolution statewide soil associations, USGS Land Use-Land Cover (LUDA), and presettlement-vegetation digital maps were combined to determine the relationships between soils and natural vegetation type, between soils and current land use, and between soils and land use change. A portion of the state was studied similarly using a high resolution data base which included digital soil series data, a more detailed presettlement vegetation map, digitized National High Altitude photography, and Landsat Thematic Mapper land use classification. Statistical correlations were conducted in both cases to determine the soil parameters which relate to current and historic land uses.

Preference: contributed paper

Evaluating abandoned pasture patch stability within a forest matrix using LANDSAT TM data and historic vegetation maps[1]

Robin Lambert Graham
Oak Ridge National Laboratory[2]
Oak Ridge, TN 37831, USA

Louis R. Iverson and Elizabeth A. Cook
Illinois Natural History Survey
Champaign, IL 61820, USA

The Great Smoky Mountains National Park, established in the southern Appalachian mountains of the United States in 1934, offers a unique opportunity to study changes in patch size and stability during the retrogression of a rural landscape to a natural landscape. Prior to establishment, several rural farm communities existed within its boundaries. Their cropland was generally aggregated in the valley bottoms; their pastures, scattered as small patches (1-30 ha) in the surrounding forested hillsides. These communities were disbanded and their associated pasture and cropland abandoned to the forces of succession. Between 1934 and 1938, the vegetation of the entire park, including the abandoned pastures on the forested hillsides, was mapped based on extensive field surveys. We mapped a portion of this same landscape 50 years later using an unsupervised classification of the spectral data from a 1984 LANDSAT satellite Thematic Mapper (TM) scene of the area. This classification created a gridded TM-landcover map of the area at a resolution of 30-m square. The ecological identity of the TM-landcover types has not been formally verified; however, knowledge of the area indicates that the TM-landcover types clearly differentiate grassland and forest. Using a Geographic Information System, we have overlaid the 1984 TM-landcover map with the historic 1938 map of the abandoned patches of pastures. Through analysis of the frequency and spatial arrangement of TM-landcovers within the historic boundaries of the pastures, we evaluated the current integrity of the pastures as patch elements providing structural diversity within the forest matrix of the landscape. The temporal and spatial stability of the patches relative to the pastures' original size, shape, and location within the landscape was also determined.

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[1]Research sponsored by NASA Contract No. NAS5-28781 to Illinois Natural History Survey.

[2]Operated by Martin Marietta Energy Systems, Inc. under Contract No.DE-AC05-84OR21400 with the U.S. Department of Energy.

ASSESSING FOREST PRODUCTIVITY IN THE GREAT SMOKY MOUNTAINS NATIONAL PARK USING THEMATIC MAPPER SPECTRAL DATA[1]

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607 E. Peabody
Champaign, Illinois

Spectral data collected by satellite have been used in a broad variety of landscape studies including mapping vegetation types, detecting temporal changes in a landscape, and identifying areas damaged by air pollution. The most recent Landsat satellites carry the Thematic Mapper (TM) spectral scanner which measures light intensity for seven spectral bands at a 30-m-square pixel resolution. With this spatial resolution and greater number of bands, it is possible for the first time to examine the vegetation mosaic of complex landscapes such as those with rapidly changing topography. If forest productivity can be related to canopy light reflectance in the wave-length bands that TM measures, then TM data could be used to detect temporal changes in forest productivity or stress associated with atmospheric deposition in mountainous terrain.

We are assessing the feasibility of using TM data in conjunction with ground-based spatial information on topography and soil characteristics to predict forest productivity. The great Smoky Mountains National Park was selected as one of our study sites because of its long history as a site for ecological research and its wide range of forest types. We are using forest productivity, soils, and topography data collected in 1982 on 128 plots, 20 x 50-m, in the western end of the park. These plots range in elevation from 400 to 1800 m and include all the forest community types found in the park except those in the high-elevation spruce-fir zone. Productivity of the plots varies by a factor of 10.

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1. Operated by Martin Marietta Energy Systems, Inc., under Contract DE-AC05-840R21400 with the United States Department of Energy. NASA Contract NAS5-28781 to Illinois Natural History Survey.

Our TM data are from a morning scene taken during September 1984. Because exact locations of the forest plots are known, we were able to extract the spectral data for pixels associated with plot locations and thus create a data set that combines plot TM spectral characteristics with plot productivity, topography, and soil type. We are now analyzing this data set with the objective of developing predictive equations of forest productivity based on TM spectral data. Thus far we have found that band 3, the ratio of band 6 to band 1, and the ratio of band 6 to band 3 are significantly correlated with productivity ($r=0.26$, 0.38, and 0.35, respectively, $P<0.001$). Future work will include relating soils, topography, and TM data to productivity and stand structure in these plots and developing an analogous data set for 20 plots in the spruce fir zone.

ESTIMATING FOREST PRODUCTIVITY IN SOUTHERN ILLINOIS USING LANDSAT THEMATIC MAPPER DATA AND GEOGRAPHIC INFORMATION SYSTEM ANALYSIS TECHNIQUES*

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and

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Oak Ridge, TN 37831

ABSTRACT

Ecological researchers have recently begun to explore the potential of remote sensing in addressing questions about the structural and functional properties of ecosystems. The objective of our research is to analyze the relationship of Landsat Thematic Mapper (TM) data and field-collected measurements of forest productivity in southern Illinois. In addition to TM data, such site characteristics as slope angle and position, soil productivity indexes, and sun radiance factors were incorporated in the analysis. Techniques for using image and geographic information system data in relation to productivity measurements taken in the field are discussed. Correlation and multiple regression results revealed the importance of TM band ratios 7:4 and 2:1 and of the woodland productivity indexes of soils in predicting forest productivity. Directions for further research in this area are suggested.

INTRODUCTION

For over a decade, Landsat data have been successfully used for mapping vegetation quantity and distribution on the landscape as well as for establishing patterns of land-cover change over time (Hoffer 1984; Colwell 1980; Woodwell et al. 1984). Satellite data have also been used in assessments of vegetation stress due to disease, insect damage, and drought (Jackson 1986; Rock et al. 1986). Productivity and biomass estimates have been made for several different ecosystems with a variety of sensors (Tucker 1980; Lulla 1981). Most of these studies have been with crops (Idso et al. 1977), grasslands (Olang 1983) or shrubby vegetation (Vinogradov 1977; Strong et al. 1985), although promising results have been reported

*This work was supported by NASA contract NAS5-28781 from the Land Processes Branch of the Earth Science Divison.

recently for coniferous forests (Fox et al. 1985; Running et al. 1986). Little work has been reported, however, that describes the potential for using spectral data to assess the productivity of deciduous forests. With the availability of the high spatial and spectral resolution from the Thematic Mapper (TM) satellites, such vegetation assessments as productivity have generally become more reliable at the community and site-specific level (Haas and Waltz 1983; Billingsley 1984).

This paper investigates the relationships of spectral data and site characteristics to the productivity of hardwood forests as measured in the field by mean annual increments in the volume of growing stock. The topograhic and soils characteristics of the sites were incorporated in the analyses using geographic information system (GIS) techniques. The statistical approach taken was exploratory; no *a priori* knowledge was assumed in order to extend current understanding of the sensitivities TM bands and band ratios to the parameters of deciduous forests. The results presented here allow us to compare the usefulness of TM data with and without GIS data in estimating the relative productivity of deciduous forests.

DESCRIPTION OF THE STUDY AREA

The southern Illinois counties included in the study area (Fig. 1) have an average of 36 percent forest cover, with a range of 22-63 percent (U.S. Forest Service 1986). These forests are part of the eastern deciduous forests which grow on sites with a wide variety of characteristics.

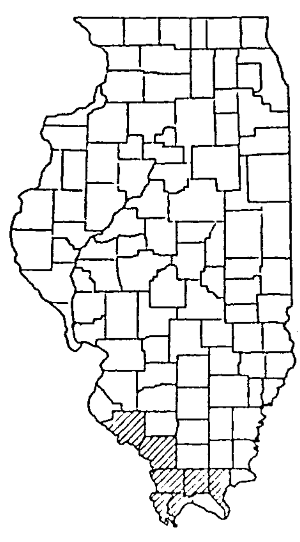

Fig. 1 Study area

Bottomland forests--primarily pin oak, cottonwood, maples, and elm--exist in the major floodplains of the Mississippi and Ohio Rivers and in the narrow valleys of smaller streams. Southern Illinois's relatively fertile bottomlands, about 100 meters above sea level, are for the most part highly productive but occasionally are limited in productivity because of poorly drained soils. The terrain of upland forest sites varies from level to steeply rolling, with deep loess to thin, rocky soils. In many areas of southern Illinois, forests persist only because steep slopes or soil conditions have limited agricultural use of the land. Most of the state's highest elevations occur here, but these reach only about 350 meters above sea level and do not significantly influence vegetation. Upland forests in the region are largely oak-hickory associations.

The study area is cold in winter and hot in summer, with average daily temperatures of 36° and 77° F, respectively. Mean annual precipitation is 42 inches. Winter precipitation results in sufficient accumulation of soil moisture and minimizes summer drought on most soils (Parks and Fehrenbacher 1968; Herman 1979; Miles 1979).

METHODOLOGY

Measurements of forest growth collected in the field, site characteristics, and radiometric data for the same ground locations were required for the statistical analysis. Digital spectral data were taken from an 18 July 1984 Landsat 5 Thematic Mapper (TM) scene covering southern Illinois (path 23, row 34). Image processing of the TM data was accomplished with the Earth Resources Data Analysis Systems (ERDAS) software on an IBM PC-AT. Ground control points were used to geo-reference five subsets of the TM scene independently to the Universal Transverse Mercator (UTM) coordinate system. Five disjunct areas were selected to maximize the number of forestry field points and minimize the quantity of TM data to be processed.

Measurements of forest growth at specific sites were obtained from the North Central Forest Experiment Station of the U.S. Forest Service. The sites were sample points measured for the 1985 Illinois Forest Inventory (U.S. Forest Service 1986). Locations of the points were referenced to the nearest meter of UTM northing and easting and could therefore be directly overlaid with the TM data. Information collected on the ground by U.S. Forest Service personnel at each point included such forest measurements as species composition, basal area, stand age, and volume of growing stock and such site characteristics as slope, aspect, and moisture regime (Doman et al. 1981). Field plots varied in size, depending on the shape of the land use patterns and on tree size, but they averaged 0.4 hectare (1.0 acre).

To allow for registration errors in both data sets, an average of the band values from nine TM pixels (a 3 x 3 block) surrounding a field point's UTM reading was used in the statistical analysis. All seven bands of TM data for the nine pixels were extracted from displayed TM images and written to an ASCII file for subsequent analysis using Statistical Analysis Systems (SAS) for Personal Computers software (SAS Institute 1985). The statistical procedures used were correlation and stepwise multiple regression.

Mean annual increment (MAI) of the trees in a plot provided an estimate of forest productivity and was calculated as the total cubic volume of hardwood growing stock at the site divided by stand age. Simple correlation and multiple regression procedures were used to test the relationhip of MAI to spectral information, which included TM raw-band values, band ratios, and transformed vegetation indexes (TVI) (Tucker 1979). These statistical tests were also conducted with standing growing stock (i.e., a biomass equivalent in cubic feet per acre) rather than MAI as the independent variable.

Ecological attributes for each plot were also entered into the statistical analysis. Slope angle of each plot, slope position (one of four quarters along a slope face), and moisture regime (xeric, xeromesic, mesic, hydromesic, hydric) were recorded at the time of plot inventory by U.S. Forest Service personnel. Sun radiation index values were calculated based on latitude, slope angle, and slope aspect (Frank and Lee 1966). Plot locations were also recorded on soil maps; this procedure allowed us to calculate a woodland productivity index for soils, referred to hereafter as soil productivity (Fehrenbacher et al. 1978).

RESULTS AND DISCUSSION

Thirty-two forest plots were located within the TM data. Mean annual increment (MAI) for these plots ranged from 8.7 to 78.7 cubic feet/ acre/year of stand age. The strongest correlation between MAI and TM band values, band ratios, and TVI's was with band ratio 7:4 (-0.46, $p = .009$). A scatter plot of MAI to band ratio 7:4 is shown in Figure 2; complete correlation results are presented in Table 1.

The relatively strong inverse correlation of MAI and band ratio 7:4 was an important preliminary result. TM Band 7, in the middle infrared (IR) range, is sensitive to total leaf-water content of the vegetative canopy. In general, Band 7 is low when the moisture level is high, due to absorption. High band 7 values in July TM data could be assumed for forest sites with low productivity because of moisture stress or less vegetative biomass at the site (Badhwar et al. 1986); the inverse correlation of MAI and Band 7 (-0.39, $p = 0.029$) supports this assumption. Band 4, on the other hand, has been shown to be directly

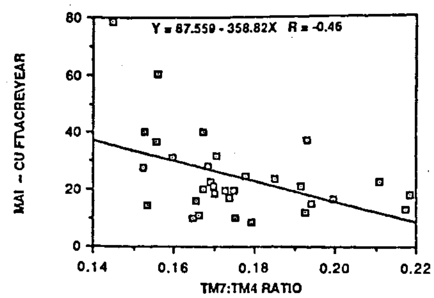

Fig. 2 Mean annual increment versus TM7:TM4

Table 1 All variables correlated with MAI

Variable	r value	Variable	r value
TM1	-0.24	TM5:TM2	-0.12
TM2	-0.27	TM6:TM2	0.20
TM3	-0.24	TM7:TM2	-0.38*
TM4	0.02	TM4:TM3	0.22
TM5	-0.30	TM5:TM3	-0.15
TM6	-0.32	TM6:TM3	0.19
TM7	-0.39*	TM7:TM3	-0.38*
TVI42	0.35*	TM5:TM4	-0.39*
TVI43	0.26	TM6:TM4	-0.13
TVI52	-0.08	TM7:TM4	-0.46**
TVI53	-0.13	TM6:TM5	0.23
TM2:TM1	-0.24	TM7:TM5	-0.40*
TM3:TM1	-0.17	TM7:TM6	-0.36*
TM4:TM1	0.17	MOISTURE	0.12
TM5:TM1	0.27	SLOPE ANGLE	-0.15
TM6:TM1	0.10	SLOPE POSITION	0.18
TM7:TM1	-0.44**	SOIL PROD INDEX	0.30
TM3:TM2	0.05	SUN RADIANCE	-0.12
TM4:TM2	0.37*		

* $p < .05$
** $p < .01$

responsive to vegetation density or biomass (Badhwar et al. 1984; Knipling 1970); however, no statistical relationship of TM Band 4 to MAI was found in our data (Table 1). Ratioing bands 7 and 4, however, accentuates differences in the spectral characteristics of site productivities and minimizes such topographic effects as shadowing (Short 1982), and the ratioed relationship was stronger than either single band (Table 1).

The site characteristics of slope angle and position, moisture regime, and sun radiance were not significantly correlated with MAI. The ranges of the topographic parameters found in southern Illinois were apparently not large enough to impact MAI, a somewhat coarse measure of productivity. Topographic influence (i.e., atmospheric variations) on TM sensor values was assumed to be negligible compared to regions with great relief ranges (Spanner et al. 1984). Moisture regimes were specified to five levels and probably did not differ enough from site to site to influence productivity. Soil productivity correlated to MAI at the 0.1 significance level. Soil productivity was of necessity estimated for several soil types because all soil types had not been rated for specific slope and erosion classes by Fehrenbacher et al. (1978). These coarse estimates and the fact that soil maps have inclusions and boundary errors that may distort the soil-forest productivity relationship account for the nonsignificant correlation.

Stepwise multiple regression techniques provided additional information for interpreting these data. All variables previously mentioned were regressed against MAI. The best single variable model was with band ratio 7:4 (r-square = 0.21, p = 0.009). Interpretation of this result is similar to that of the previously described simple correlation. Soil productivity was the second variable introduced into the model and it, when included with band ratio 7:4, improved the model (r-square = 0.30, p = 0.006). In the absence of extreme topographic variances in the study area, soil productivity apparently assumed a major role with forest MAI. When band ratio 2:1 entered the stepwise model, the three variables--band ratio 7:4, soil productivity, and band ratio 2:1--had an r-square of 0.39 (p = 0.002). In previous studies, TM data provided the most information when at least a mid-IR, near IR, and visible band were considered in the analysis (Badhwar et al. 1984; Haas and Waltz 1983; Sheffield 1985; Dottavio and Williams 1982). The three-variable model includes all of these. Also, acknowledging the role of site characteristics in predicting productivity, the inclusion of soil productivity in the best multiple regression model is important and underscores the desirability of including geographic information system data in such analyses. Collinearity diagnostics showed that multicollinearity was not a problem among these three variables, thereby indicating that the model is robust. A plot of actual versus predicted MAI is shown in Figure 3. Models with more than three variables were not considered because one or more additional variables failed to contribute significantly to the model due to collinearity.

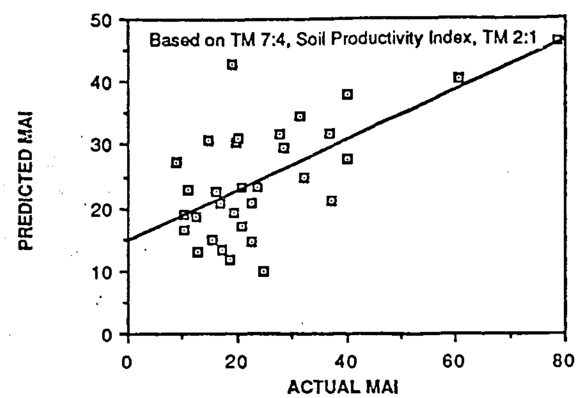

Fig. 3
Predicted MAI from the best three-variable model

Although excessive scatter was found in the three-variable predictive relationship (Fig. 3), these preliminary results are encouraging since TM data from only one date was used. Further, variables used in the significant regression models were inexpensive to obtain relative to the costs of collecting ground data. The predictive relationship may prove to be adequate for regional studies of relative forest productivity when examining, for example, carbon cycling; however the relationship is not tight enough for reasonable estimates of productivity at particular ground locations.

All correlation and regression statistics previously presented with MAI were also run using biomass measurements for the plots. The biomass relationships were either not significant or not as strong as those run with MAI, a finding that suggests that site productivity and not just vegetation density or biomass is being predicted in the statistical relationships discussed.

Important follow-up issues in this research pertain to temporal and regional interpretability of results and to procedures for improving the prediction accuracy of the model. For instance, would the productivity data used in this study from southern Illinois have improved correlation and regression results if we had had TM data from an additional date? In regions with more extreme variations in topography and climate, might slope, sun radiance, or rainfall have replaced soil characteristics as critical site variables? We are currently addressing these questions in companion research.

CONCLUSIONS

TM band ratio 7:4 correlated most strongly with hardwood forest productivity in southern Illinois. Using multiple regression, we found that the three-variable model based on band ratio 7:4, on soil productivity, and on band ratio and on band ratio 2:1 was the best predictor of productivity. However, the confidence intervals for the prediction were too wide for the model to be used for accurate measurements of specific sites.

Several procedures are currently being devised that may improve these encouraging preliminary results, including multitemporal TM data analysis, the inclusion of additional GIS variables, the testing of other field measurements of forest productivity, and comparisons of results from other regions of the United States. Models that reliably esimate forest productivity from TM and GIS variables could be used to spatially generalize point sample data of field-measured forest productivity, thereby producing more accurate and less costly regional assessments. Additionally, TM-based models can serve to calibrate coarser remote sensing data (e.g. AVHRR) to achieve a considerable reduction in data volume for global carbon studies important to current and future ecological research.

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